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Contractor: University of Hawaii

Objective: Stigmatic Spectrograph Study

Submitted by

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A. Summary of Objectives

Objectives of the research may be summarized as development of a stigmatic spectrograph of nominal dispersion of 1 A/mm and resolution of 0.01 A, useful in the range from 1000 A to 3000 A, and of sufficient speed and compactness to be suitable for use in rocket and satellite spectroscopy.

General application of such instrumentation to the spectroscopic aspects of space research is anticipated. Such application includes:

(1) detailed spectra of ultraviolet solar and stellar spectra;

(2) line profiles of ultraviolet emission lines;

(3) measurements of vertical distribution of terrestrial atmospheric constituents;

(4) investigation of the solar continuum below 1800 A;

(5) absolute measurement of solar and stellar wavelengths;

(6) laboratory measurement of absorption cross section of gases, and products of photochemical processes;

(7) interstellar absorption spectroscopy.

B. Summary of Progress

(1) Construction of a vacuum test chamber has been completed. The unit consists of a 12" x 54" x 22" rectangular chamber pumped by a 6" diffusion pump backed by a 47 cu. ft./minute mechanical pump. Auxiliary equipment now available for use with this chamber for testing and application of the spectrograph being designed includes:

(a) A 10-kilowatt current-regulated power supply for operation of a hollow cathode light source.

(b) Alternating current supply at 0.5 amps and 3000 volts for operation of a hydrogen capillary discharge source.

(c) Vacuum measuring equipment consisting of a hot filament ionization gauge, a cold cathode gauge and an Alphatron gauge.

(d) A water-cooled hollow cathode source.

(e) A Hanovia capillary windowless light source.

(2) Principal components of a thermal evaporation unit for preparation of efficient ultraviolet reflecting surfaces have been assembled.

(3) Preliminary echellegrams have been obtained using a breadboard arrangement of the optical components in the vacuum test chamber. Qualitative verification of basic design principles have been obtained with this instrument.

(4) A precision scanning laboratory instrument of 48" focal length has been assembled and mechanical and electronic systems tested. Necessary modifications and improvements of this instrument have been completed.

(5) The basic design principles of precision high resolution spectrographs and scanning spectrophotometers for rocket and satellite spectroscopy have been determined. Specifications for a rocket instrument have been completed and construction and evaluation of some components are underway.

C. Progress During The Report Period

Considerable progress toward perfecting the mechanical and electronic systems of the laboratory instrument was made. This instrument is now operable. Preparations are being made to install the instrument in the vacuum chamber for further evaluation.

A number of electromechanical servomechanisms are required to properly use and align the instrument optics. All servo systems have been designed and are in operation. These servo systems are described below.

1. Order Selection

To select the order to be observed, the angle of the grating must be set with an accuracy of one part in 100,000. In the present design the operator selects the desired order digitally by means of rotary selector switches. The number to be dialed for any particular order is read from a chart which is determined experimentally. Direct selection by actually setting the switches to the order number is a refinement that will be evaluated and possibly included in new designs.

In essence, the servo system is an automatically-balanced resistance bridge. The operator sets one arm of the bridge when an order is selected. The servo positions a potentiometer, which is mechanically coupled to the grating, to balance the bridge. In this manner the grating can be precisely positioned to any desired angle. Major components are shown in the block diagram, figure 1.

Tests have shown the design to be adequate for present purposes, but a special enlarged following potentiometer that will improve the resolution about ten times has been designed. Inquiries will be sent to vendors to determine the feasibility of the potentiometer modification.

Autocollimating System

The translation and rotation of the echelle and grating are effected by a mechanical linkage, but the final trim is achieved by rotating the echelle with a servo system that is controlled by an optical reference. A beam of light about one inch in diameter is reflected from small mirrors fastened to the major optical components of the spectrograph. After striking all surfaces, the beam is detected by a pair of photocells imbedded in clear plastic on opposite sides of a sheet of thin metallic foil. When all optical components are correctly aligned, the beam of light will be split by the foil and the photocells will be illuminated with equal brightness. When alignment is not correct, one photocell will detect more light than the other; therefore, the resistance of the photocells will be different.

The photocells are used as two arms of a resistance bridge. When the bridge becomes unbalanced, the servo system rotates the echelle until the bridge is balanced. Thus the beam of light is kept focused on the edge of the foil, assuring that the spectrograph optics are correctly aligned. Figure 2 is a simplified block diagram of the autocollimating servo.

Entrance Slit Alignment

As the echelle rotates, the entrance slit must be rotated, in a plane perpendicular to the incident beam, through an angle T as determined by the following equation:

$$\tan T = -K \sin \gamma$$

where K is a constant determined by the echelle characteristics and γ is the rotation angle of the echelle. A special mechanical linkage having an input of γ and an output of T solves the above equation continuously.

To eliminate the load upon members of the mechanical linkage and to provide for smoother operation, a servo follower has been incorporated between two members of the linkage. It is a contactor servo shown in simplified form in figure 3. The servo motor drives a synchro transmitter and the associated synchro receiver positions the entrance slit.

Design specifications for the rocket instrument have been finalized to a sufficient extent to permit delineation. These specifications are appended to this report. The specifications refer to an optimal instrument. Compromises on some specifications will be made as design proceeds.

Progress in the writing and testing of computer programs for data handlings and profile correction was made. A report on this aspect of the research will be included in the next report.

D. Personnel

During the period reported here the following individuals participated in various phases of this work.

Howard C. McAllister, Principal Investigator
George Yokatoke, Machinist
Edward Schafer, Machinist
Robert Perry, Laboratory Technician
David F. Swift, Electronics
Michael Yamamoto, Graduate Laboratory Assistant
Gary Ing, Undergraduate Laboratory Assistant
Ronald Iwata, Undergraduate Laboratory Assistant

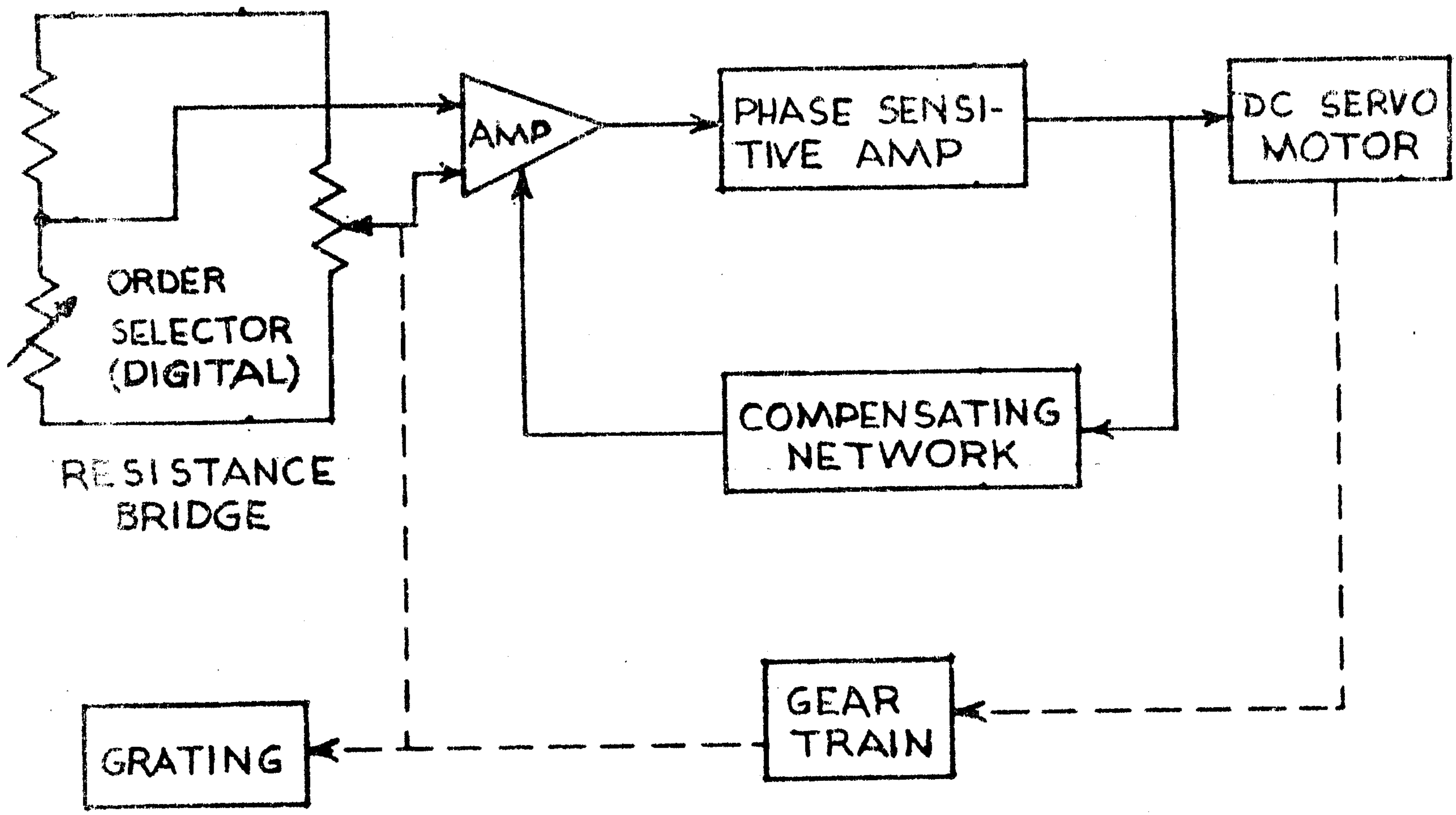


FIG. 1 ORDER SELECTION SERVO

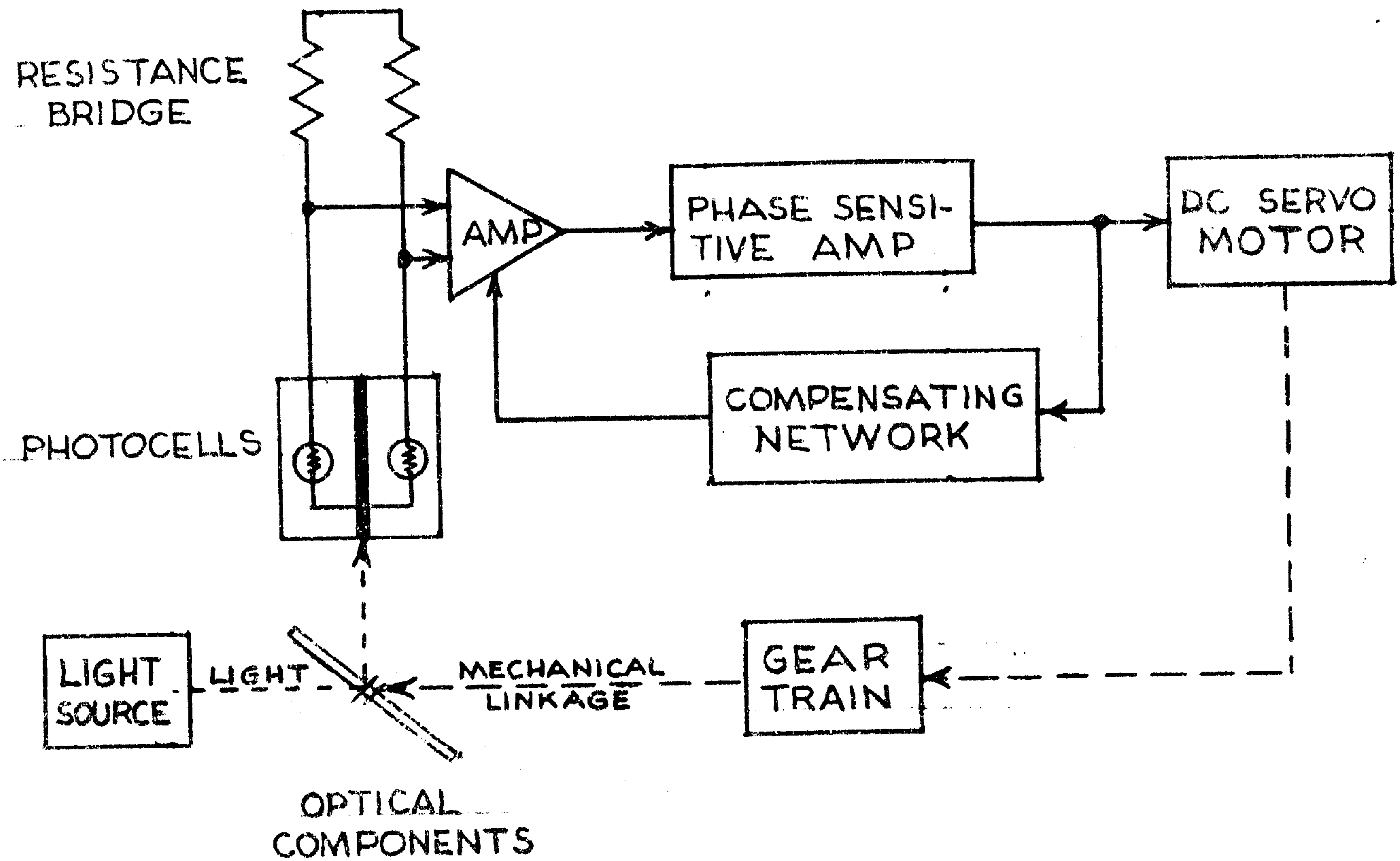


FIG 2. AUTOCOLLIMATION SERVO

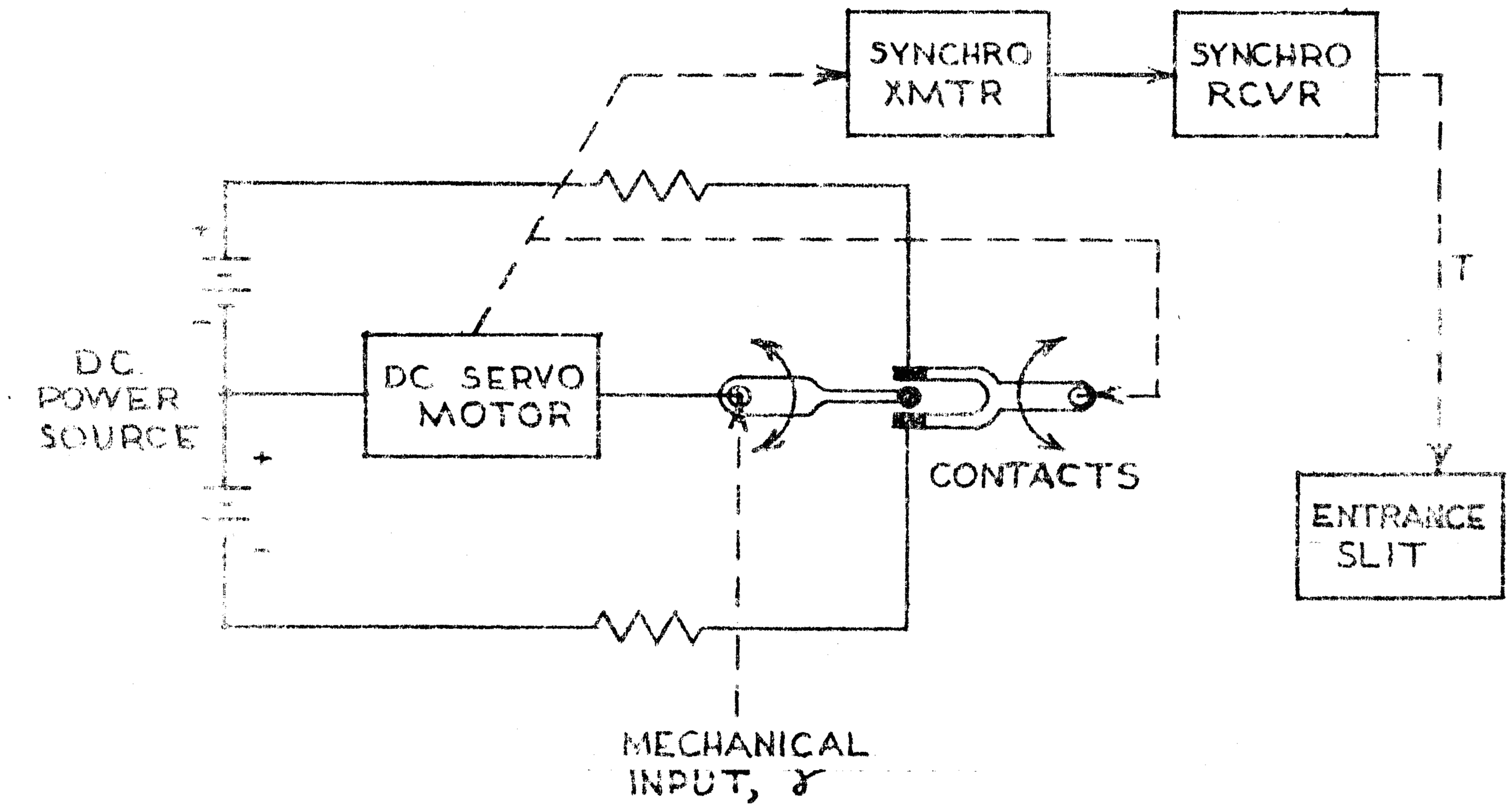


FIG. 3. ENTRANCE SLIT ROTATION SERVO

APPENDIX

HIGH RESOLUTION SCANNING MONOCHROMATOR
PRELIMINARY DESIGN SPECIFICATIONS

PART I. DESIGN THEORY

The grooves of the ruled echelle have the form indicated in Fig. 1a. Gratings of this form have the useful property that the grating constant can be made effectively continuously variable[1,2] merely by rotating the grating about the axis Y shown in Fig. 1a. If the grating is rotated through an angle γ about this axis, as shown in Fig. 1b, the grating equation can be written for small $\alpha - \beta$ as $2t \cos \gamma - s\theta = m\lambda$, where t is the depth of the groove, s, the height of the groove, and $\theta = \alpha - \beta$ as shown in Fig. 1b. For $\theta = 0$, this gives

$$\lambda = \frac{2t \cos \gamma}{m} . \tag{1}$$

Therefore, for a given order m, any wavelength, within a range defined by practical limits and the size of γ, can be set at $\theta = 0$.

The wavelength range incident on the ruled echelle must usually be limited to a wavelength range given by the free spectral range $F = \lambda^2/2t \cos \gamma$ if such an arrangement is to be useful. This can be effected by predispersion, filters, or internal cross dispersion. The latter method gives rise to an instrument of remarkable versatility.

If the light from the echelle strikes a grating (G in Fig. 1b), the rulings of which are perpendicular to the ruling of the echelle, and observations are made in a direction parallel to the incident beam as shown, the grating equation applied to G becomes, since $\alpha' + \beta' = 2\gamma$,

$$\lambda = 2d_g \sin \frac{\alpha' - \beta'}{2} \cos \gamma, \tag{2}$$

where d_g is the grating constant.

1. H. Greig and W.F.C. Ferguson, J. Opt. Soc. Am., 40, 504 (1950).

2. N.A. Finklestein, J. Opt. Soc. Am., 41, 179 (1951).

Equations (1) and (2) give

$$m = \frac{t}{d_g} \frac{1}{\sin \frac{\alpha' - \beta'}{2}} \tag{3}$$

which is independent of γ for the order observed in the direction parallel to the incident beam. Thus an order can be selected by rotating G to the appropriate value of α'. The wavelength, at $\theta = 0$ and in the specified direction, is then $\lambda = \lambda_m \cos \gamma$, where $\lambda_m = 2t/m$. Wavelengths ranging from $\lambda_m \cos \gamma_o$ to $\lambda_m \cos \gamma$, will pass successively by $\theta = 0$ as γ is increased from γ_o to γ, the various λ_m being selected by setting G to the appropriate value of α'. The grating G must be linked to the echelle in such a way that the grating rotates at the same rate as the echelle and such that during γ scanning the grating travels parallel to the incident beam at a rate consistent with interception of the light from the ~~echelle~~ echelle.

The lines of the echelle are not perpendicular to the parallel beam of light incident on the echelle. As a consequence, the image of the entrance slit is not parallel to the entrance slit.[1] The rotation T, in a plane perpendicular to the incident beam, of the image of the entrance slit is related to the rotation γ of the echelle by $\tan T = -2r \sin \gamma$, where $r = t/s$.

The optical layout for a symmetric instrument of this type is shown in Fig. 2. Fig. 3 shows the layout of a laboratory prototype instrument which has been constructed. In this instrument the correct motion of the optical components is effected by mechanical linkage as shown. Servo-mechanical correction of the motion of the optical components is effected by means of an autocollimating system (not shown). Figure 4 shows a preliminary conceptual drawing of the rocket instrument. A more fully developed drawing of the rocket instrument is shown in Fig. 5. In the rocket instrument the motion of the optical components will be controlled servo-mechanically rather than by the direct mechanical linkage shown in Fig. 3.

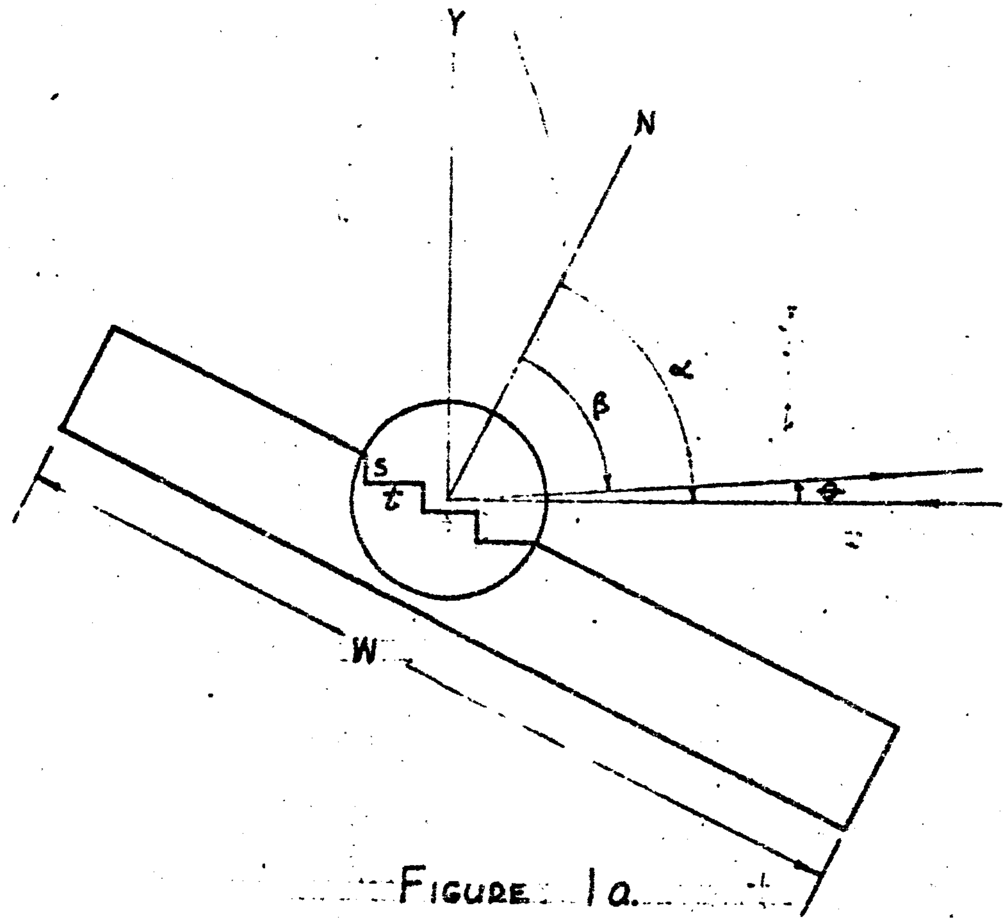


Figure 1a.

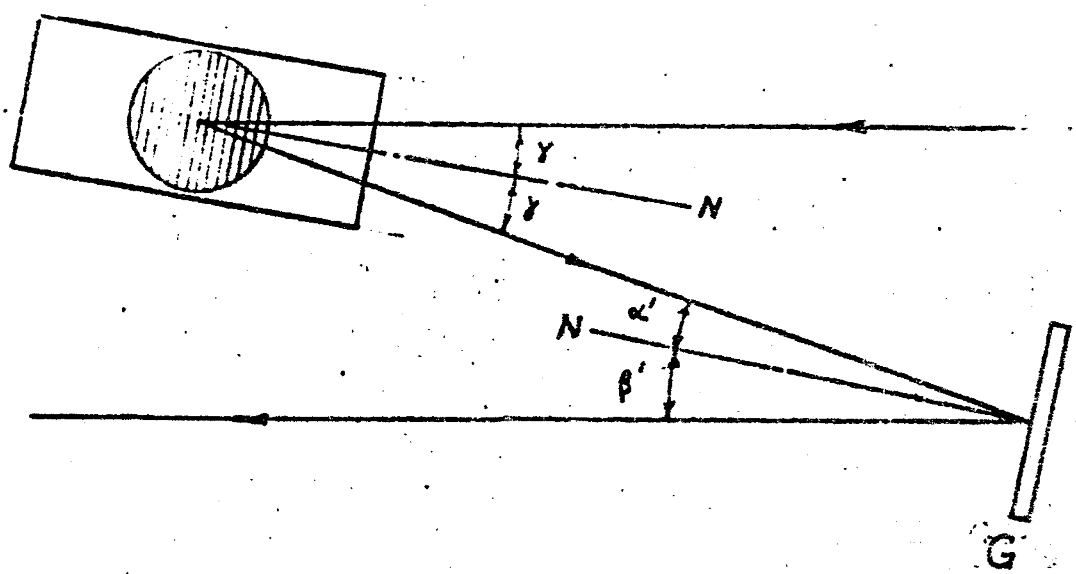


Figure 1b.

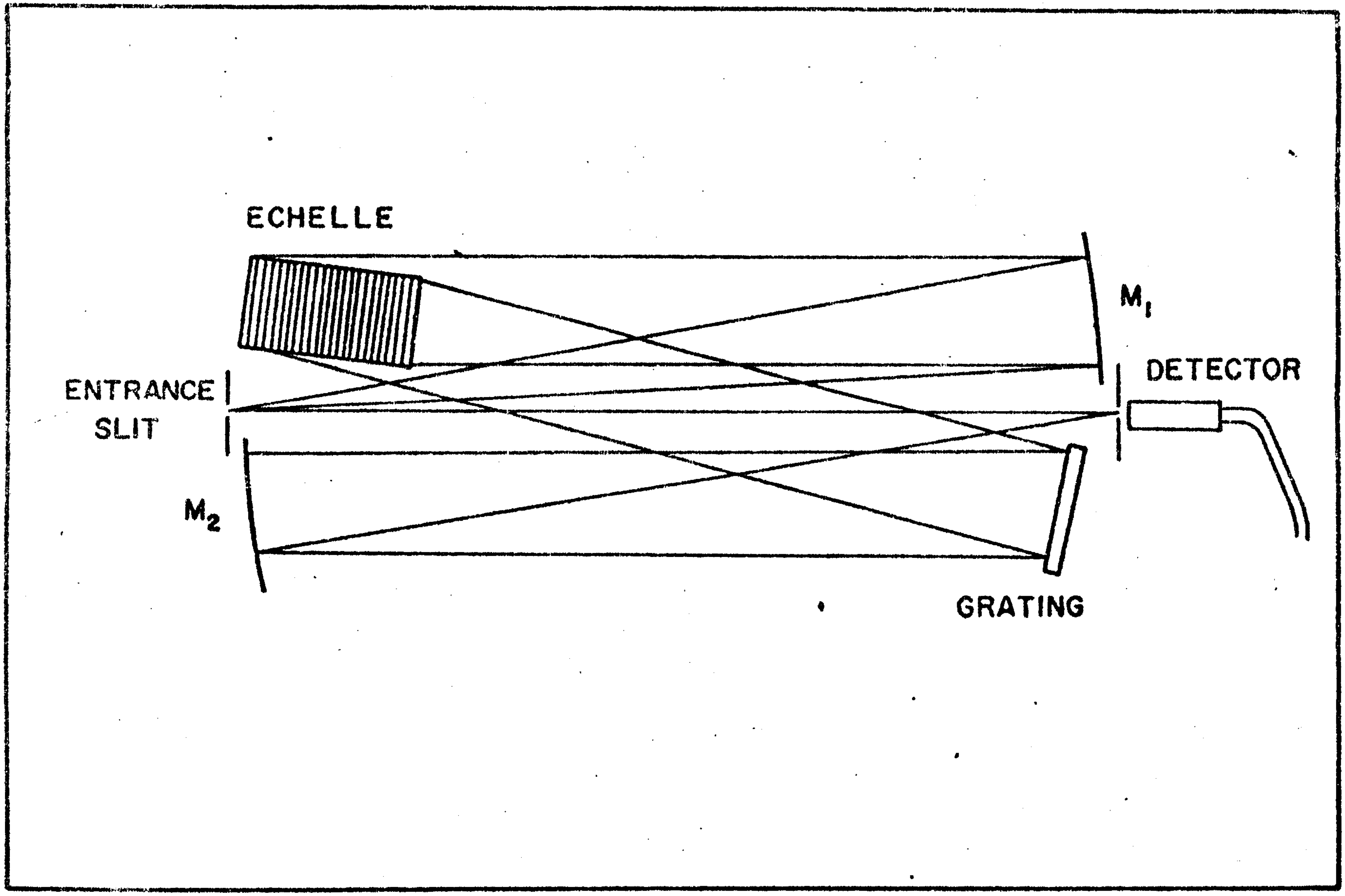


Figure 2

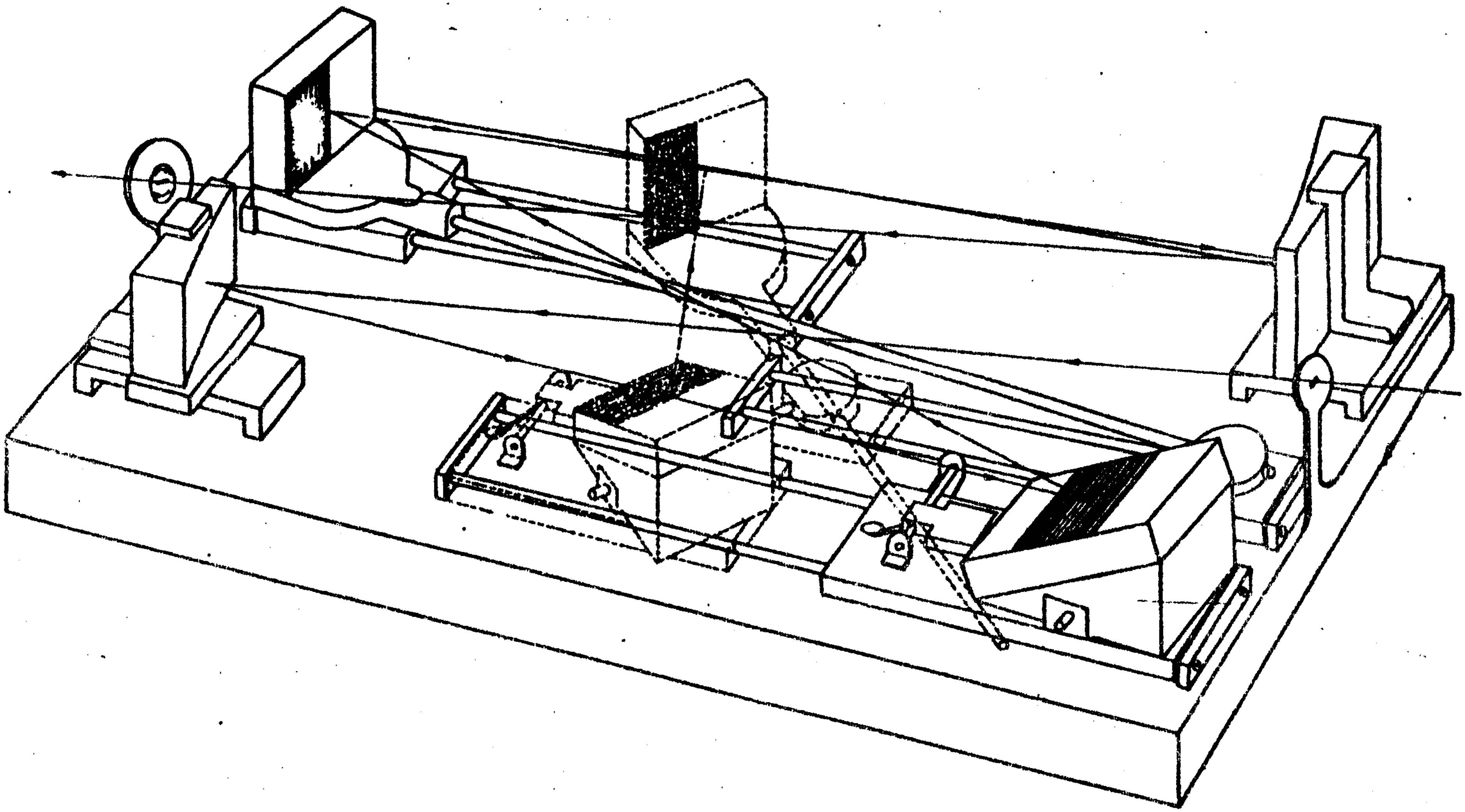


Figure 3

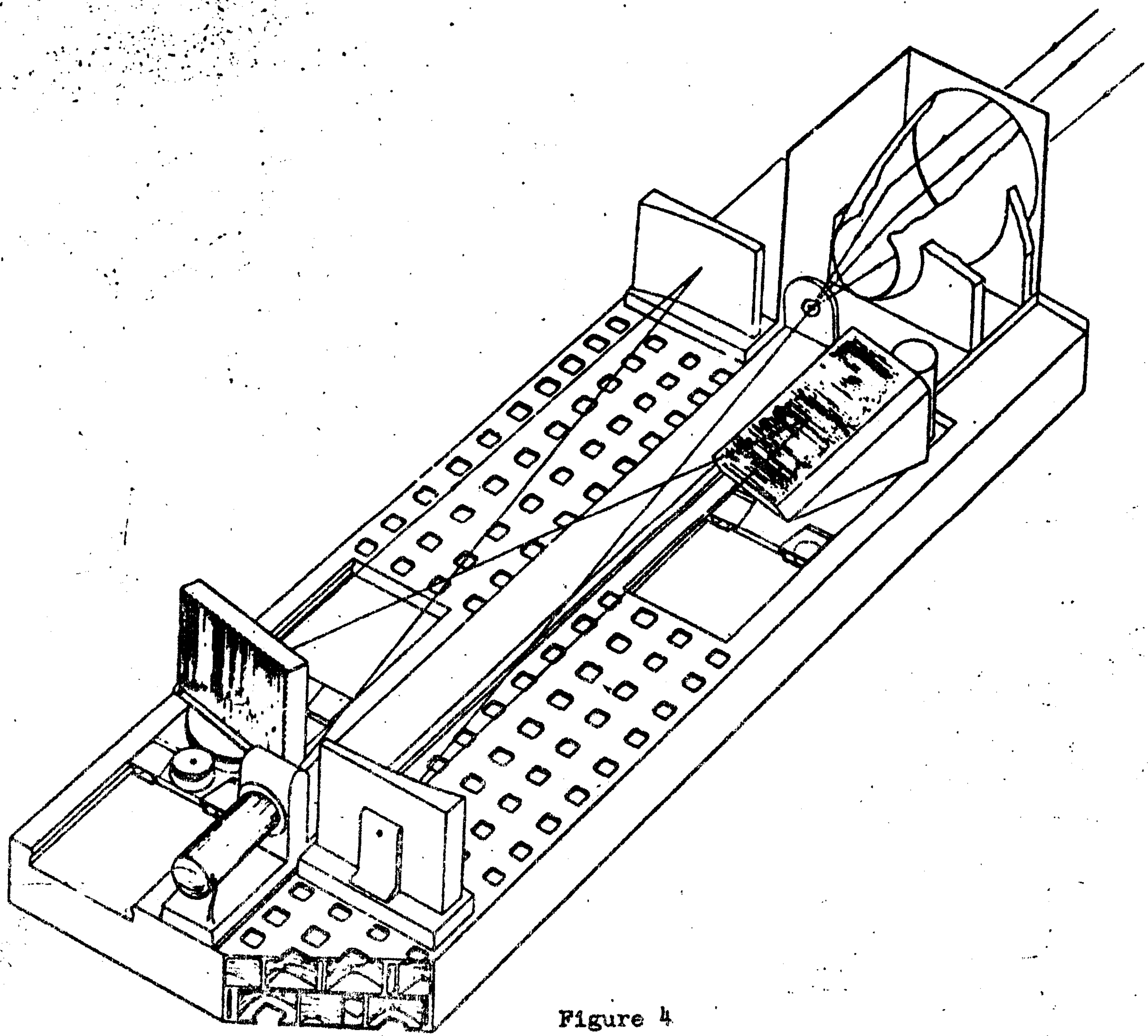


Figure 4

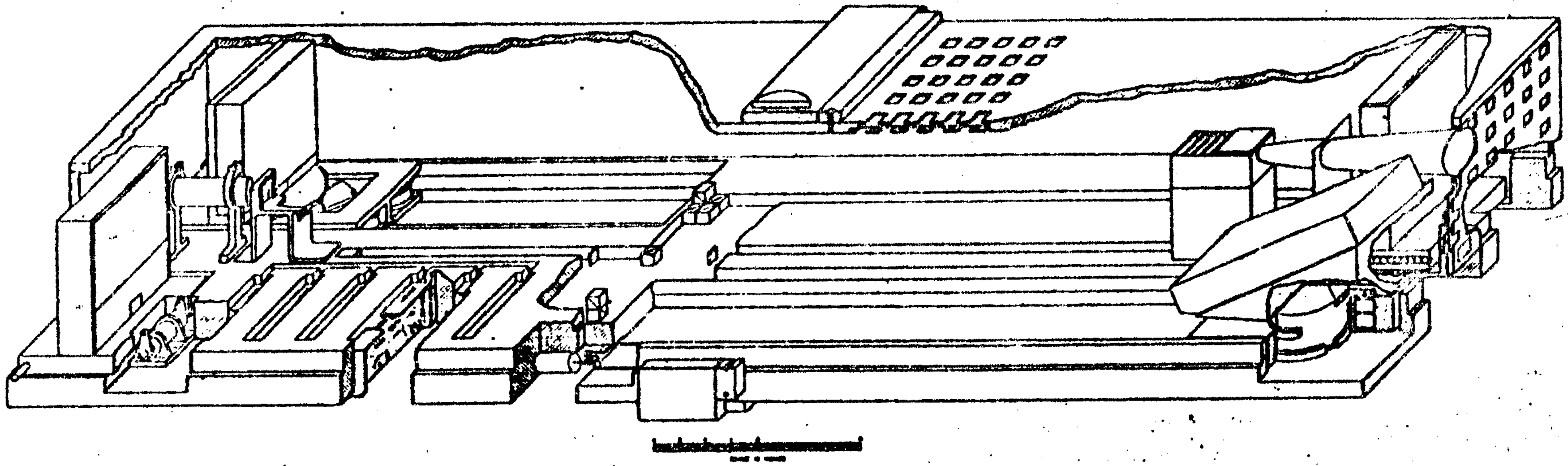


Fig. 5

PART II. SYSTEMS: DEFINITIONS AND SPECIFICATIONS

For design purposes the instrument is divided into the major interrelated systems described below.

A. Scanning System

The SCANNING SYSTEM consists of certain parts of the grating and echelle assemblies and the associated driving mechanisms. The linear and rotational motion of the grating and echelle assemblies will derive from the SCAN COMPUTER SYSTEM. The linkage between the SCAN COMPUTER SYSTEM and SCANNING SYSTEM will be effected by a closed loop servo system so designed and executed as to assure correct linear motion to 0.1%. Linear position of the grating and echelle platforms will be determined by rectilinear linear potentiometers imbedded in the instrument base. Correspondence between the position of the grating and echelle platforms and positions specified by the SCAN COMPUTER SYSTEM will be effected servo-mechanically. The driving mechanism for the two platforms will take one of two alternative forms: (a) a chain drive, or (b) a rack and pinion drive. The relative linear motion will be such as to provide maximum scan range consistent with the theoretical basis for the scanning operation described in Part I.

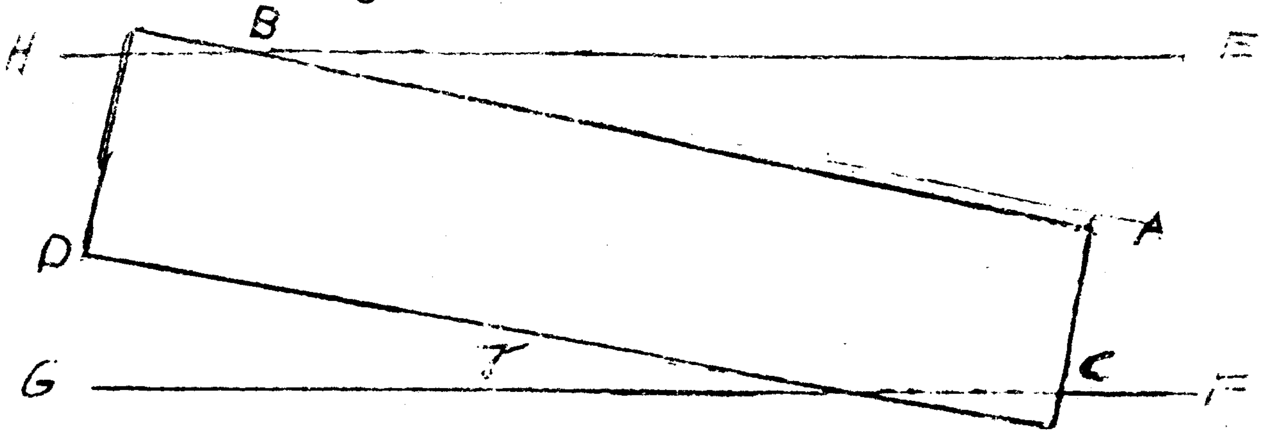
The possibility of incorporating variable scan speed related to the photomultiplier output signal will be studied. The feasibility of fast scan motion for the purpose of obtaining rapid access to any desired spectral region will also be investigated.

Angular position of the grating and echelle will be determined by means of circular linear potentiometer segments. The linkage between the SCAN COMPUTER SYSTEM and the SCANNING SYSTEM will be effected by a closed loop servo system so designed and executed as to assure that the rotational motion of the echelle and grating will be correct to 10^{-5} radians when this motion has been corrected by the ALIGNMENT SYSTEM.

Properties of the OPTICAL SYSTEM make it desirable that the instrument be capable of scanning with the linear position of the grating fixed. Linear motion of the grating assembly is not strictly a part of the scanning operation but is incorporated in order to extend the scan range of the instrument.

B. Scan Computer System

The essential features of the SCAN COMPUTER SYSTEM are shown in the diagram below.



The relative linear position of the echelle and grating are defined by points C and B of this diagram. The angular positions of the grating and echelle scanning platforms are defined by the angle γ of this diagram. As the rectangular laminar ACDB is rotated about the point A, which is midway between the parallel lines HE and GS, the relative linear motion of the grating and echelle platforms is prescribed by the motion of the points B and C along the parallel lines HE and GB.

The corresponding angular motion of the grating and echelle is prescribed by the change in the angle γ. This part of the SCAN COMPUTER SYSTEM has one degree of freedom whereas two degrees of freedom are necessary to effect the maximum scan range required by the specification of the SCANNING SYSTEM. The second degree of freedom required corresponds to the movement of point A along a line parallel to and midway between parallel lines HE and GF. Incorporation of motion of point A in this part of the SCAN COMPUTER conflicts with the need to keep the SCAN COMPUTER compact. However, translation of the point A, with γ fixed, causes points B and C to move equally in the same direction. Thus simple translation of the echelle and grating platforms in the same direction by equal amounts is equivalent to translation of the point A in the SCAN SYSTEM. The desired motion of the echelle and grating platform can then be effected by adding equal translations of the echelle and grating platform to the relative translation prescribed by this part of the SCAN COMPUTER SYSTEM. This addition will be a part of the SCAN COMPUTER SYSTEM. Scanning with grating platform stationary can be effected by causing the speed of the equal translations of the echelle and grating to be equal and opposite to the speed of point C of the SCAN COMPUTER.

C. Order Selection System

The ORDER SELECTION SYSTEM will be capable of rapid selection of any order in any sequence by appropriate rotation of the order selection platform of the grating assembly. The required accuracy of the ORDER SEEECTION SYSTEM is 10^{-5} radians. The selection of order will be initiated by the CONTROL SYSTEM. Two methods of effecting the proper rotation of the order selection platform will be evaluated:

(a) Using a circular segment of a linear potentiometer to measure the angular position of the order selection platform, the correct position of the order selection platform being established by closed loop servo comparison with appropriate calibrated fixed resistances. The fixed resistance appropriate to each order will be selected by a switching mechanism controlled by the instrument CONTROL SYSTEM.

(b) Digital determination of angular position of the order selection platform by counting revolutions of the driving motor. The electronic revolution counter will count to preset counts specified by the instrument CONTROL SYSTEM.

In either system preflight and inflight verification and correction of the ORDER SELECTION SYSTEM by means of reference to fiduciary positions of the order selection platform will be included.

The order selection system will also generate the information necessary for setting the slit lengths of the entrance and exit slits of the DETECTOR SYSTEM.

D. Alignment System

The ALIGNMENT SYSTEM serves to measure the relative orientation of the four optical components of the OPTICAL SYSTEM. This will be effected by passing a collimated light beam through the system in such a manner that it is reflected at least once from plane mirrors mounted on or attached to the optical components. This collimated light beam will be imaged on a detector array which will detect errors in relative orientations of the optical components. A self aligning system will thus be effected, assuring correct optical alignment in spite of possible errors generated by the SCANNING SYSTEM, the SCAN COMPUTER SYSTEM, the STRUCTURAL SYSTEM, and the OPTICAL SYSTEM.

Alignment errors will be servo mechanically corrected by tilting the collimating mirror and changing the angular position of the echelle scanning platform. The tilting mechanism of the collimating mirror and the focusing mechanism of the camera mirror are part of ALIGNMENT SYSTEM.

E. Electrical System

The electrical system includes all electronic subsystems, including detectors, motors and associated gearing, power supplies, input to telemetry, integration with requirements of the mechanical motions and so forth. In as much as the ELECTRICAL SYSTEM overlies all aspects of the instrument, specifications of the ELECTRICAL SYSTEM derive from the requirements of the other systems, as well as from requirements of the experiments.

F. Structural System

The STRUCTURAL SYSTEM involves the basic design of the component parts of the instrument, particularly those which are to be machined from stock materials. These include the instrument base, instrument case, echelle and grating assemblies, mirror bases and mounts, and components of the DETECTOR and ALIGNMENT SYSTEMS.

The structural assemblies will be for the most part machined from aluminum alloy 6065-T651 and magnesium AZ31-B. Specifically, the instrument base and case of Rocket Instrument Number 1 will be made of aluminum. The internal components of this instrument, particulary those contributing appreciably to the moment of inertia of the instrument, will be machined from magnesium. The base, case, and internal components of rocket instrument number 2 will be machined from magnesium. Weight reduction of the base, case, and internal components will be effected to the extent possible by removing excess material in such a way as to leave an interlaced I-beam structure. The five sides of the case and the base will interjoin by means of precision light-tight joints. The reproducibility of positioning of these pieces will be assured by an adequate number of position pins. Helicoils will be used in all demountable screw holes. Vents for prevention of trapped gas in screw holes will be provided as well as vents for escape of gas from the instrument.

The design target for weight of the instrument is 40 ±5 lbs. and for moment of inertia, about the geometrical center and perpediculer to the 7 inch dimension of the 7" x 11" x 48" rectangular parallelpiped case-base, plus internal components, is 9000 ± 1000 lb-in^2.

The average density of the instrument will be 0.3 gm/cm^3 and the average density of components of the instrument will be 0.65 gm/cm^3. Assuming uniform distribution of mass in a 7" x 11" x 48" instrument, the moment of inertia of the instrument about the azimuth direction would be 8,000 lb-in^2. However, the location of the principal optical components near the ends of the instrument contribute at least 5,500 lb-in^2 to the moment of inertia, leaving (using 9,000 lb-in^2 for the total moment of inertia) 4,500 lb-in^2 for the structural components, excluding optics, or an average density of the structural components of approximately 0.3 gms/cm^3 or about 12% of the density of aluminum, requiring considerable ingenuity in design of the STRUCTURAL SYSTEM.

G. Detector System

The detector system will consist of the following subsystems: (1) Exit slit assembly with provision for control of the slit length, slit width and slit rotation, the film transport, supply and storage assemblies, the light baffle assembly, the photomultiplier and associated mounting structures. (2) Entrance slit assembly with provision for control of the slit length, slit width and slit rotation, shutter mechanism, filter mechanism, light baffles, collecting optics and associated mounting. (3) Mechanical analog computer to control the rotation of the exit slit or/and the entrance slit. Integration of the DETECTOR SYSTEM with the other systems of the instrument will be considered part of the DETECTOR SYSTEM.

Preliminary specifications of the subsystems and assemblies of the DETECTOR SYSTEM are delineated below.

a. Slit Assembly

1. Rotation of slit assembly will be correct to 10^{-4} radians. This accuracy includes errors introduced by the analog computor. Specifically, the relation between slit angle T and echelle rotation γ is

$$\tan T = -4 \sin\gamma$$

The computer will generate T from γ and T will be correct to 10^{-4} radians. Slit jaws will be parallel and coplanar to 1 micron.

2. The slit width will be controlled by the instrument control system. Setting will be incremental, the signal for changing the slit width by one increment in either direction being derived from the

control system. The accuracy of the slit width setting will be 10% of the slit width. Verification of the slit width setting should be incorporated.

3. The slit length will be accurately controlled to 2% of the slit length. Slit length will be effected by direct continuous control by the order selector. Verification of the slit length setting should be incorporated.

4. Associated mounting structures for the slit assembly includes convenient removal and replacement.

5. A calibrating light will serve for in-flight verification of photomultiplier-electrometer calibration. This verification is dependent on accurately known slit width and slit length.

6. Slit jaws with a photosensitive surface facing the incoming light may be used. This will measure the light level adjacent to the slit, such measure being useful in effecting correction for close scattering.

b. <u>Exit Light Baffle</u>

The exit light baffle system will be designed to operate in two modes.

1. Scanning Mode

   In this mode the light baffle system will close to the smallest size consistent with interception of all on-axis light from the camera mirror plus off-axis light arising from the length and width of the slits.

2. Photographic Mode

   In this mode the light baffle system will open to the maximum size consistent with satisfactory photographic operation. This size will be limited by general scattered light.

The initiation of change of mode will derive from the instrument CONTROL SYSTEM.

c. Film Cassette Assembly

This assembly consists of supply cassette, take-up cassette, film plane, transport mechanism and transport control system.

- The supply and take-up cassette will be such as to minimize film abrasion. The length of film accommodated shall be of the order of 30 feet. Movement of the film will be effected by means of a film transport system which moves the film a distance of 2 inches in not more than one-tenth second. The movement of the film will not be effected by windup of the take-up spool but by a claw or sprocket mechanism acting at both ends of the film plane. Tension in the film will be avoided both during transport and while at rest. Strict attention to conformation of the film to the prescribed film plane is required. Transport of the film will be initiated by shutter mechanism causing transport to occur immediately after the shutter closes. Stopping of the film transport will be effected by suitable perforations in the film and associated detectors. Film stopping will in turn activate the shutter mechanism to effect the next exposure of a sequence. Serious consideration will be given to the feasibility of obtaining photomultiplier monitoring between exposures. This will require a rapid camshaft movement of the camera mirror to bring the image into focus on the slit during film transport. Exact location of the exit slit relative to the spectrum recorded in the previous exposure will be needed if such a monitoring is used.

Transport and dwell of the film will be monitored by telemetry. The shutter control of film transport may be overridden by the control system.

d. Film Punch and Die Assembly

The film punch and die assembly will provide punching of sprocket perforations, punching of transport control performations, punched holes for photomultiplier viewing and such other requirements as may develop. Film prepared by the punch and die assembly will be loaded directly on the supply cassette. Precautions to avoid film abrasion will be taken.

e. Mechanical Analog Computor

The mechanical analog computer will continuously effect the equality

$$\tan T = -4 \sin \gamma$$

where T is the slit tilt angle and γ is the echelle rotation. γ is the input and T the output of this computer. T so generated will be transmitted to the exit slit, effecting rotation of the exit slit. A closed loop servo will be used, so designed and executed that the error in slit position will not exceed 10^{-4} radians.

f. Entrance Assembly

The entrance slit has the same specifications as the exit slit with regard to length and width control. Rotation of the entrance slit may or may not be required depending on further investigation. Tentatively it will be assumed that rotation will be included. Thus the exit slit and entrance slit systems will be identical and interchangeable.

The shutter mechanism will be included in the entrance assembly. The shutter mechanism will be capable of logrithmic exposure sequencing, effecting automatically exposure sequences such as 1, 2, 4, 8, 16 time units, the 1 time unit being variable and specified by the instrument CONTROL SYSTEM. The number of exposures in a sequence will be specified by the CONTROL SYSTEM. Control will be returned to the CONTROL SYSTEM after each exposure sequence. The sequential exposure feature may be overridden by the instrument CONTROL SYSTEM.

An automated filter assembly will be included in the entrance assembly allowing up to six filters to be inserted just in front of the entrance slit. The selection of filter will be determined by the instrument CONTROL SYSTEM.

Provision for measuring the fluctuation of light flux through the entrance slit will be made. This measurement will provide means of compensating for pointing control system jitter.

The light collecting system will consist of a short focal length parabola, a lens, a reflecting mirror, or a reflecting grating. The possibility of incorporating any one of these possible collectors shall be included in the design.

H. Optical System

The OPTICAL SYSTEM consists of the collimating mirror, echelle, grating and camera mirror. These optical components are tentatively to be formed from fused quartz, weight relieved by using an egg crate construction as produced by the Corning Glass Works. The mirrors will be either spherical, mounted in a Zerny-Turner arrangement, or off-axis parabolas. Both types of mirrors will be acquired and the choice made empirically. The grating will be a 12,000 line/cm Bausch and Lomb replica grating blazed for 1500 angstroms. The echelle will be either a 75 line/mm or 300 line/mm Bausch and Lomb replica echelle. All optical components will be aluminum coated with a magnesium fluoride protection coating.

The optical components will be as large as the instrument can accommodate. A vibration-tested, semi-resilient mounting of the optical components will be used.

I. Control System

The CONTROL SYSTEM will control the sequential functions of the instrument. These functions include order selection, slit width setting, filter selection, focus alteration, shutter operation and scan operation. The CONTROL SYSTEM will be based on the use of punched program tape or equivalent method designed to provide maximum flexibility in sequencing instrument operation.

Integration of the control requirements of the DETECTOR SYSTEM with the control requirements of the total instrument will be necessary.

J. Peripheral System

The PERIPHERAL SYSTEM will include all equipment and procedures not integral to operation of the instrument. These include external control and monitoring of instrument operation for the purpose of preflight evaluation, as well as internal operation and monitoring to evaluate inflight performance. Maintenance procedures and equipment, including repairs and replacements, will be a part of the PERIPHERAL SYSTEM.